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# Small angle Thomson scattering for femtosecond X- ray pulses

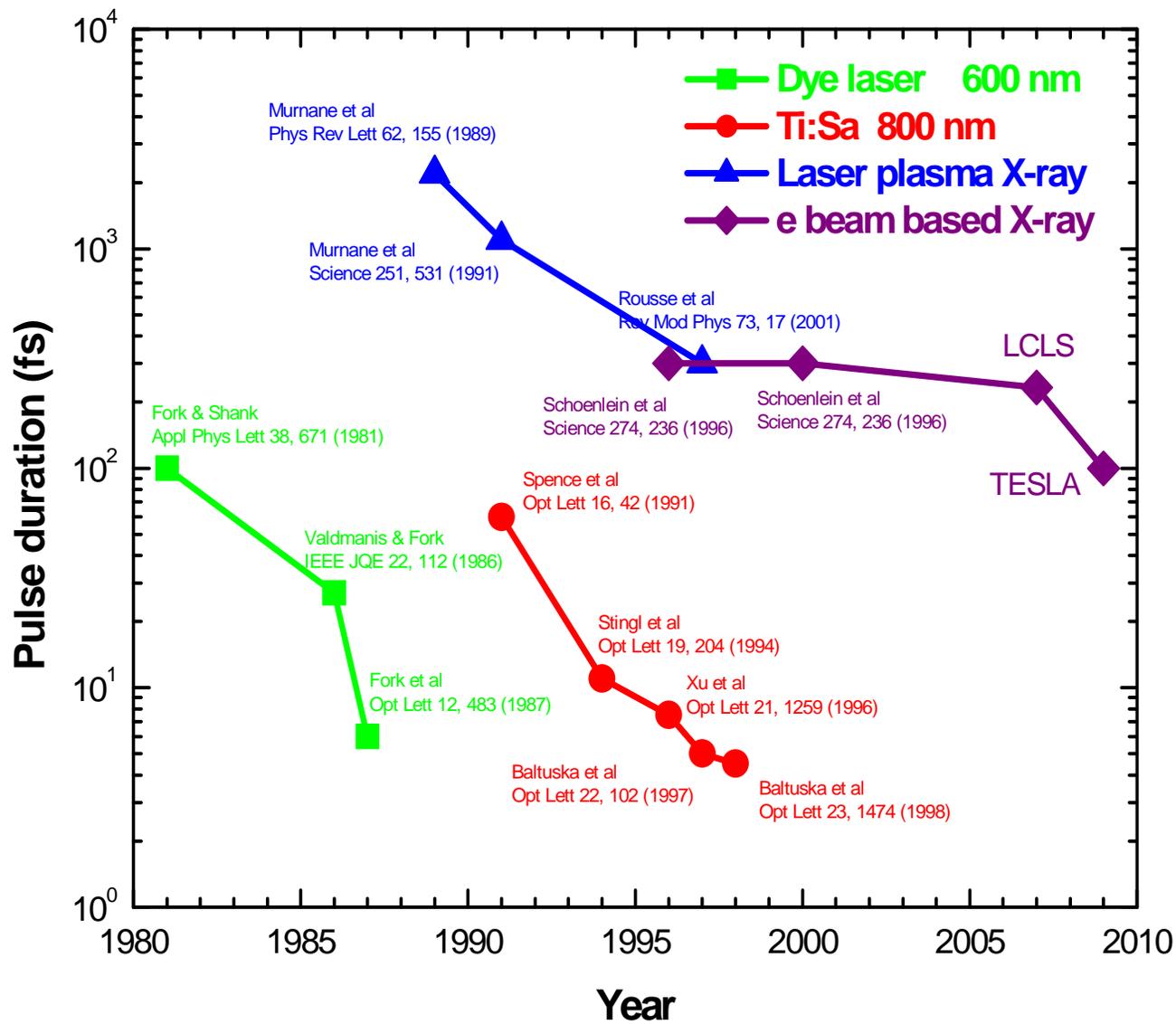
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Advanced Photon Source, Argonne National Laboratory

*Supported by the U. S. Department of Energy, Office of Basic  
Energy Sciences*

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# Introduction: to become faster

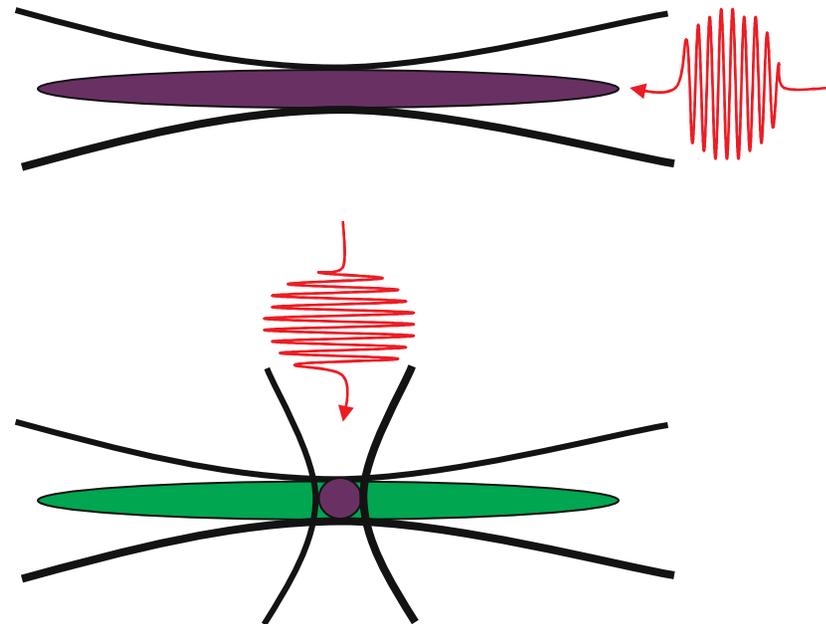


## Thomson scattering for ultrashort X-ray pulses

- Thomson scattering
  - Double Doppler frequency shift

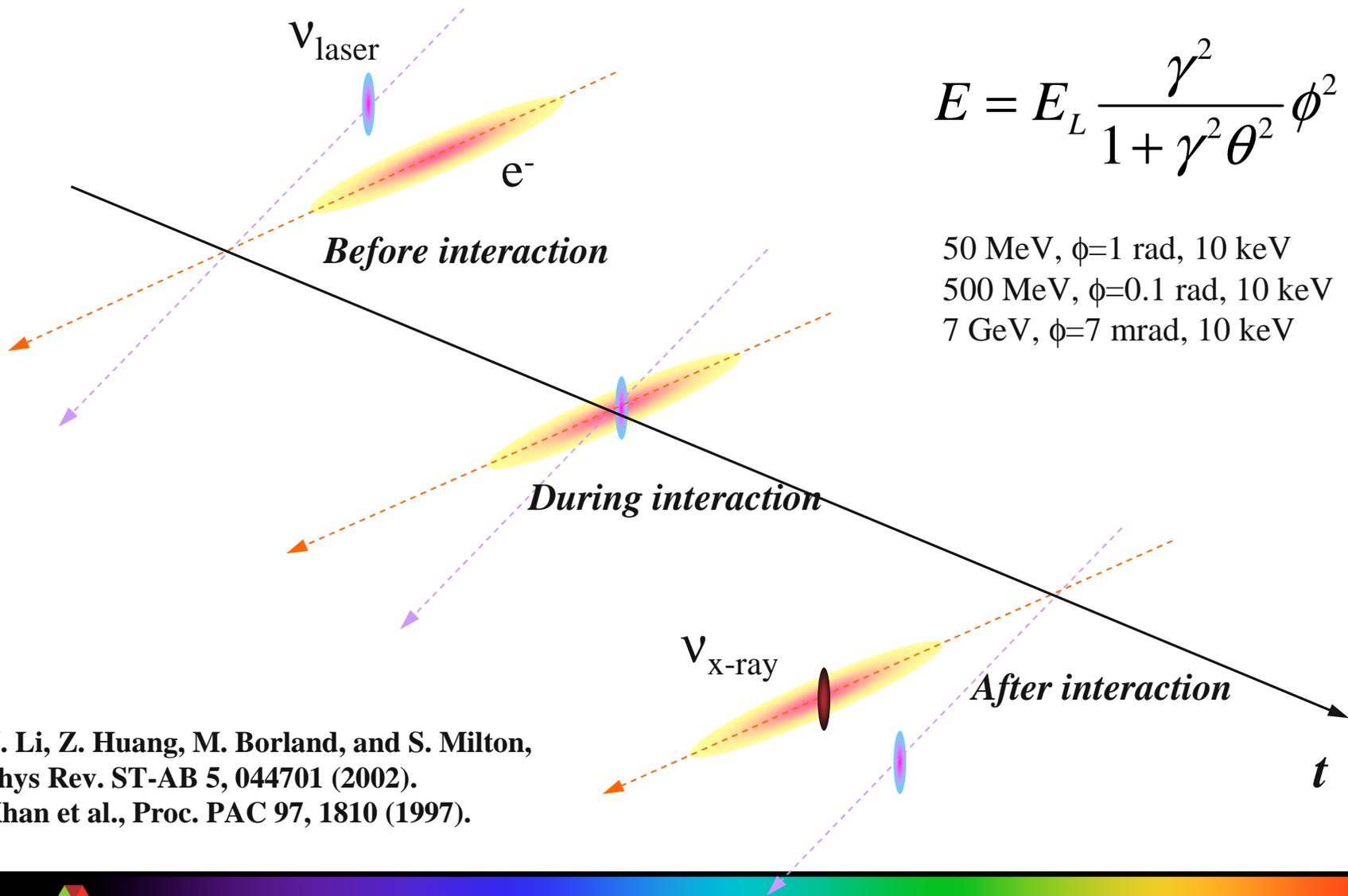
$$E \approx E_L \frac{2\gamma^2}{1 + \gamma^2\theta^2} (1 - \cos\phi),$$

- Pulse durations, with a ultrafast laser
  - Head on: bunch length
    - $E_x=4\gamma^2E_p$ , for 1 eV photons
      - 50 MeV, 40 keV
      - 500 MeV, 4 MeV
      - 7 GeV, 200 MeV
  - 90 degree, Bunch cross section
    - $E_x=2\gamma^2E_p$ , for 1 eV photons
      - 50 MeV, 20 keV
      - 500 MeV, 2 MeV
      - 7 GeV, 100 MeV



# Small-angle Thomson scattering

## X-ray duration determined by laser pulse duration



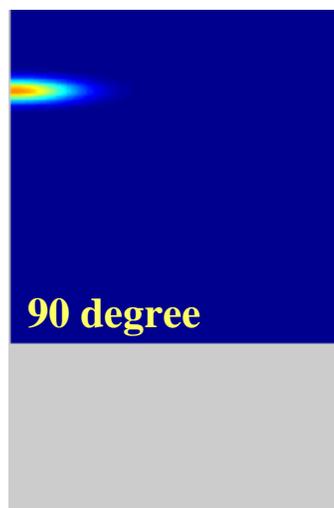
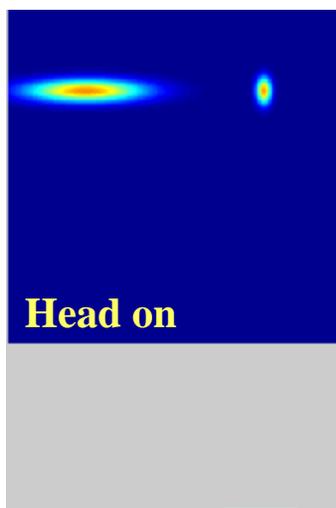
$$E = E_L \frac{\gamma^2}{1 + \gamma^2 \theta^2} \phi^2$$

50 MeV,  $\phi=1$  rad, 10 keV  
 500 MeV,  $\phi=0.1$  rad, 10 keV  
 7 GeV,  $\phi=7$  mrad, 10 keV

- Y. Li, Z. Huang, M. Borland, and S. Milton, Phys Rev. ST-AB 5, 044701 (2002).
- Khan et al., Proc. PAC 97, 1810 (1997).

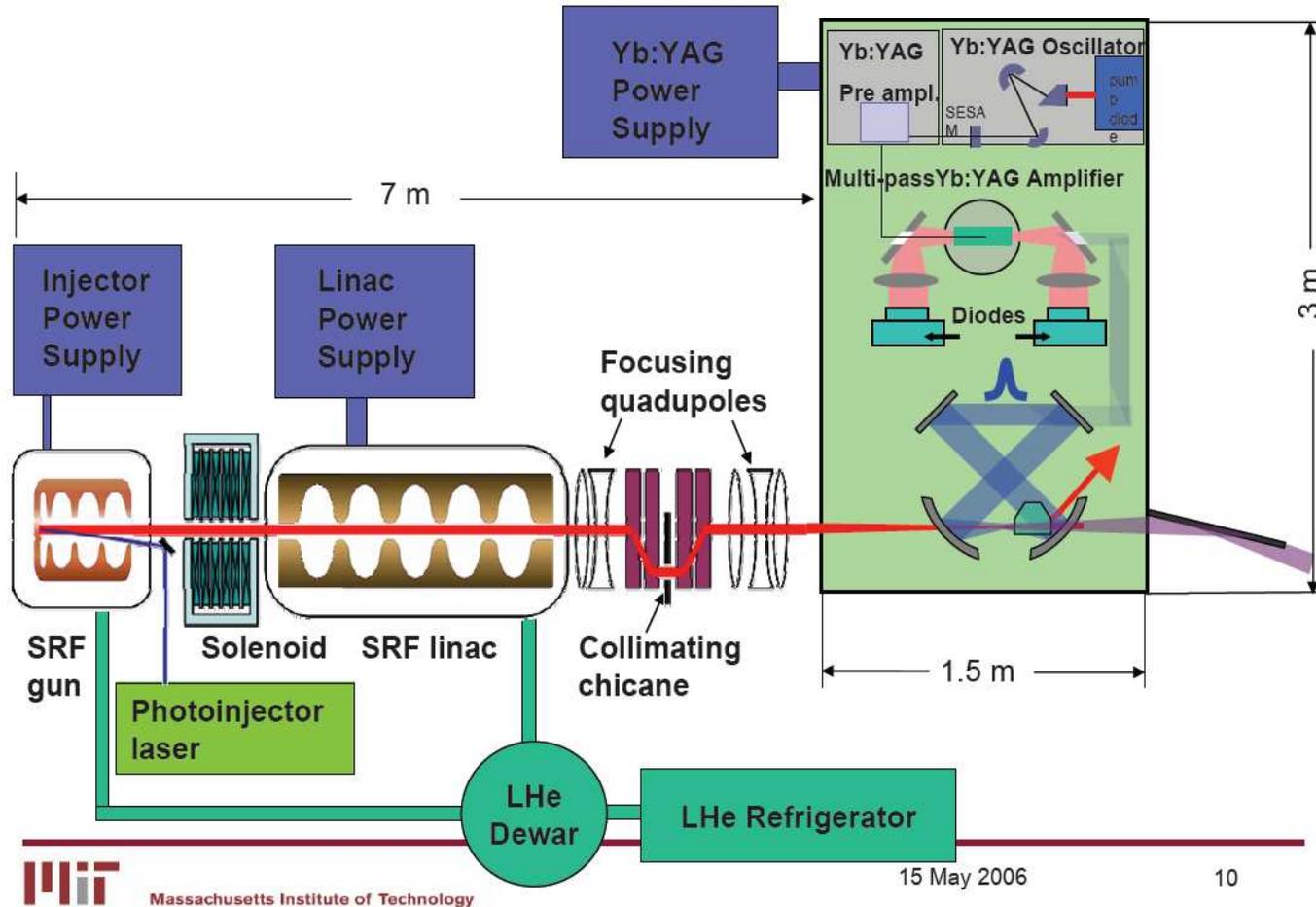
# Movie time

## Scattering Schematic



# A head on case at MIT

## MIT Inverse Compton Source Concept



# Small angle Thomson scattering

## X-ray pulse duration estimate

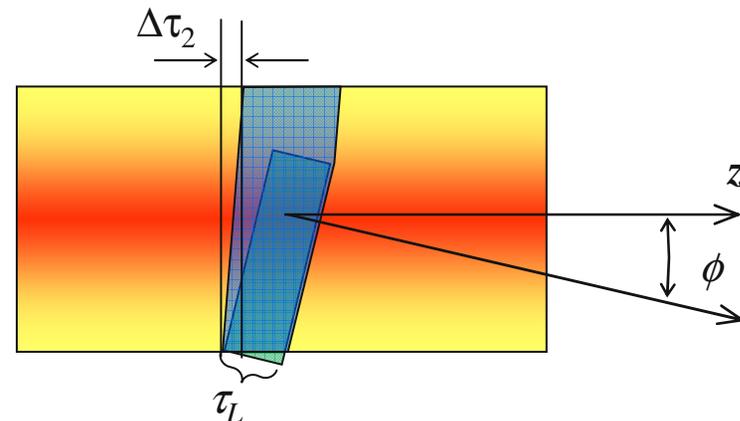
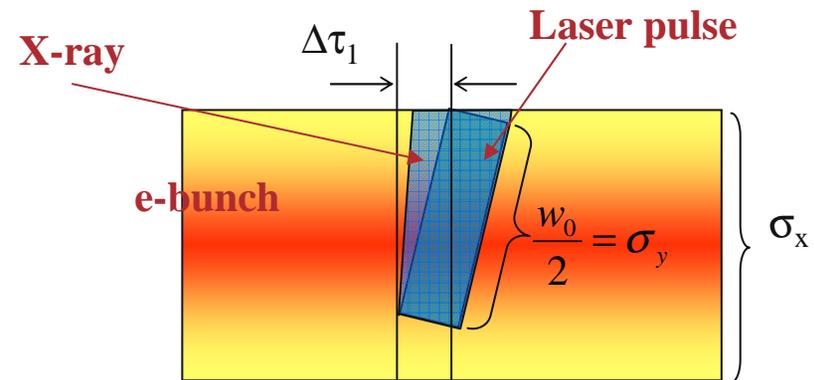
$$\Delta\tau_1 = (1 - \cos\phi) \frac{w_0 \cos\phi}{2c \sin\phi} - \frac{w_0 \sin\phi}{2c} \approx -\frac{w_0}{4c} \phi$$

$$\Delta\tau_2 = (1 - \cos\phi) \frac{\sigma_x}{c \sin\phi} \approx -\frac{\sigma_x}{2c} \phi$$

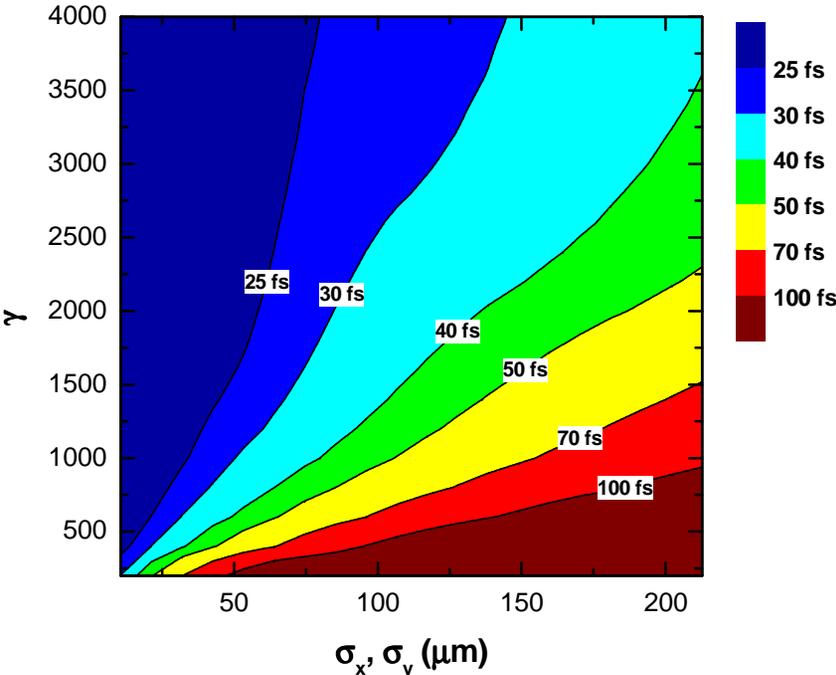
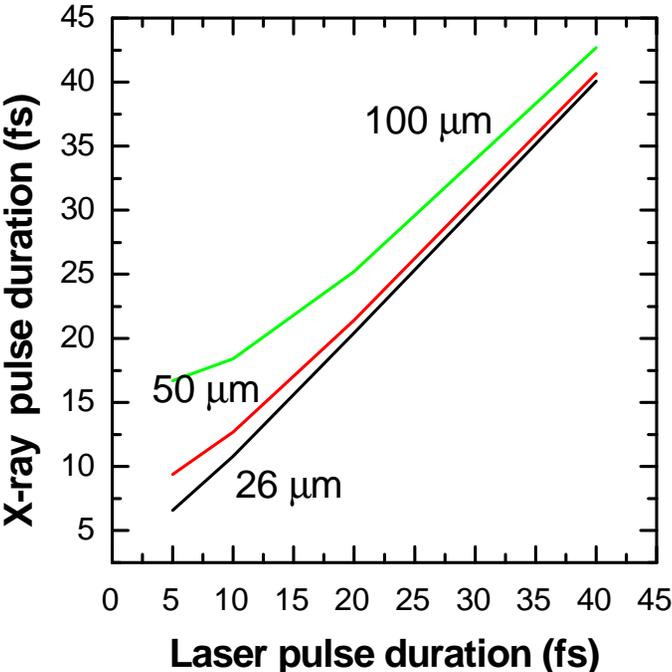
$$\tau = \left( \frac{\tau_L^2}{\cos^2\phi} + \Delta\tau_1^2 + \Delta\tau_2^2 \right)^{1/2}$$

$$= \tau_L \left[ 1 + \left( 1 + \frac{\sigma_x^2 + \sigma_y^2}{4\tau_L^2 c^2} \right) \phi^2 \right]^{1/2}$$

$$\tau \approx \tau_L$$



# X-ray pulse duration



Photon energy      8-keV

Photon energy	8-keV
Bunch energy	650 MeV
$\lambda_L$	800 nm
$\Phi$	60 mrad
$\tau_L$	20 fs

# Scattering efficiency and bandwidth

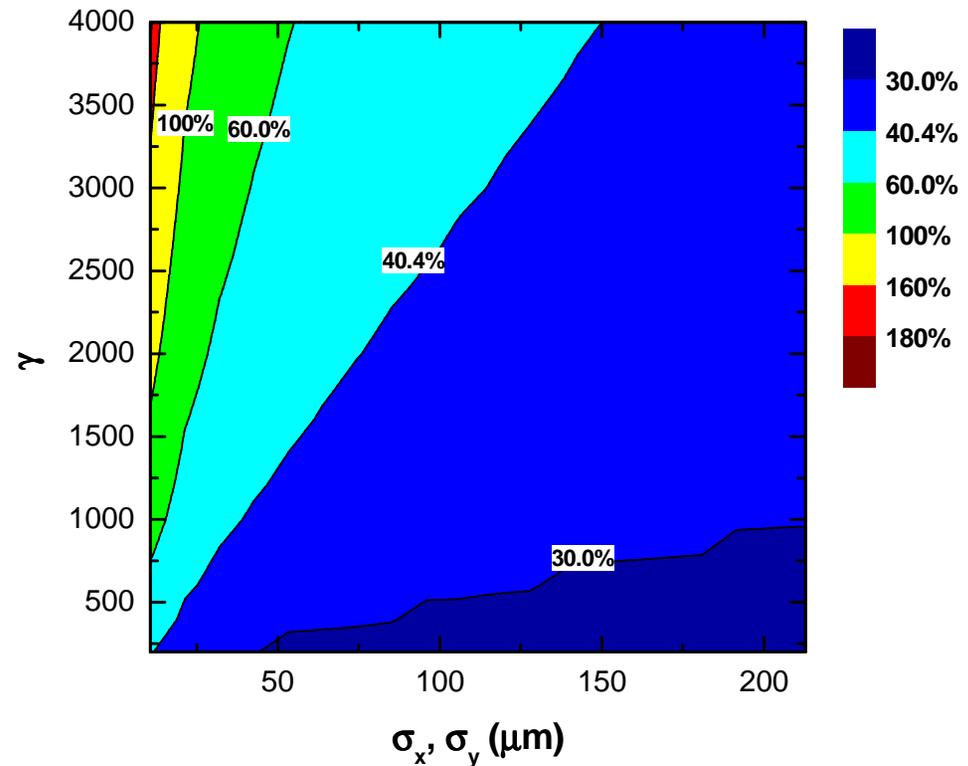
Total photon production

$$n \approx \frac{\Sigma_0}{4\pi} \frac{N_p N_e}{\sigma_y \sigma_z} \phi$$

For small enough  $\phi$ , the angle-integrated bandwidth is

$$\left( \frac{\Delta E}{E} \right)_{\text{int}} \approx 2 \frac{\sigma_\phi}{\phi} = \frac{\lambda_L}{2\pi\sigma_y\phi}$$

## Full bandwidth



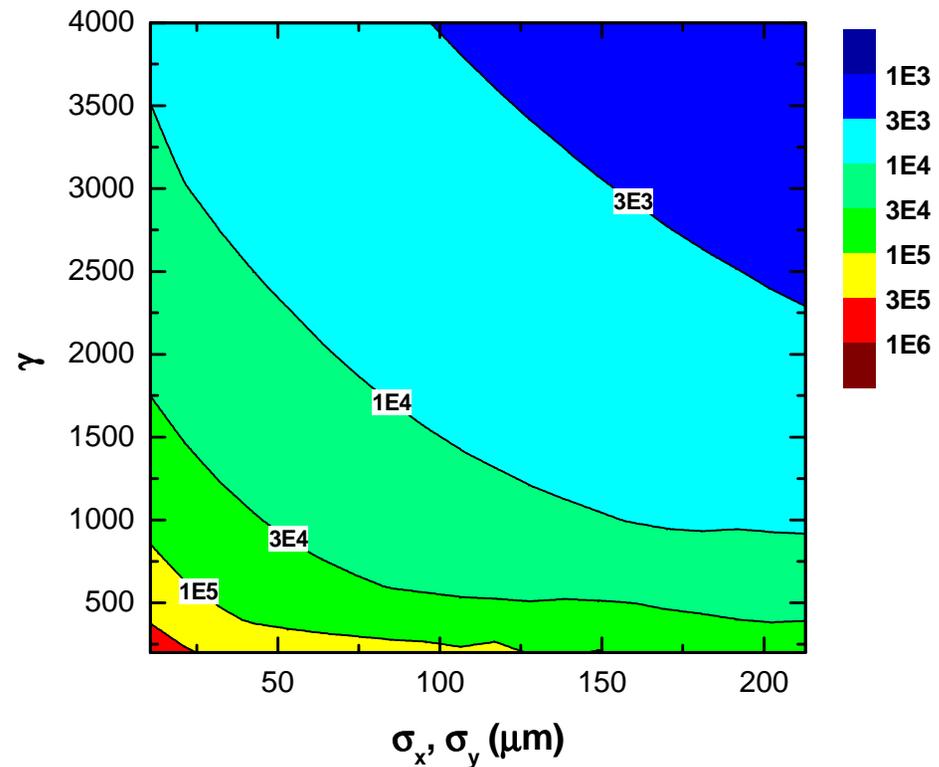
# X-ray photon flux

$$\begin{aligned}
 F &\approx \frac{1}{2\pi} \frac{n}{\tau} \frac{\delta_{BW}}{\left(\frac{\Delta E}{E}\right)_{\text{int}}} \\
 &\approx \frac{\Sigma_0}{4\pi} \frac{N_p N_e}{\sigma_z \tau_L} \frac{\delta_{BW}}{\lambda_L} \phi^2 \\
 &\approx \frac{\Sigma_0}{4\pi} \frac{N_p N_e}{\sigma_z \tau_L} \frac{\delta_{BW}}{\lambda} \frac{1}{\gamma^2}
 \end{aligned}$$

Where we used

$$\phi = \frac{1}{\gamma} \sqrt{\frac{E}{E_L}} = \frac{1}{\gamma} \sqrt{\frac{\lambda_L}{\lambda}}$$

## X-ray photon flux (photons s<sup>-1</sup> 0.1% bandwidth)

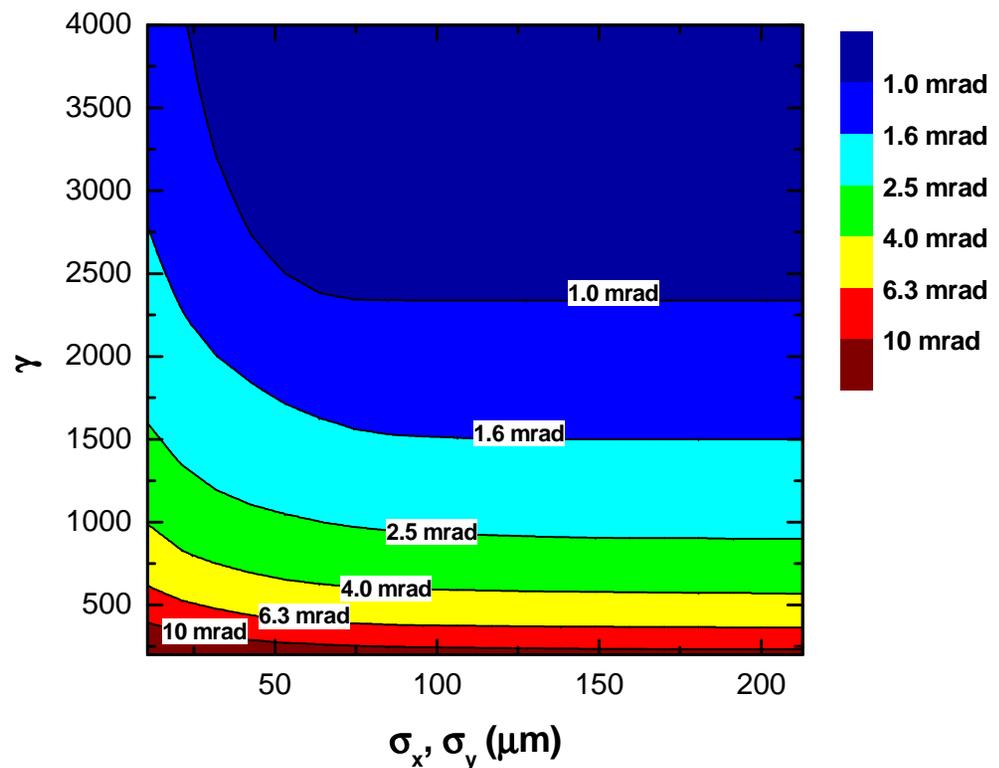


# X-ray divergence

The divergence is the convolution of the Lorentz contraction effect and the divergence of the e-bunch:

$$\phi_{x,y} \approx \left( \frac{1}{\gamma^2} + \sigma_{x',y'}^2 \right)^{1/2}$$
$$\approx \frac{1}{\gamma}$$

## X-ray divergence



# X-ray spectral brightness

$$B = \frac{F}{(2\pi)^2 \varphi_x \varphi_y s_x s_y}$$

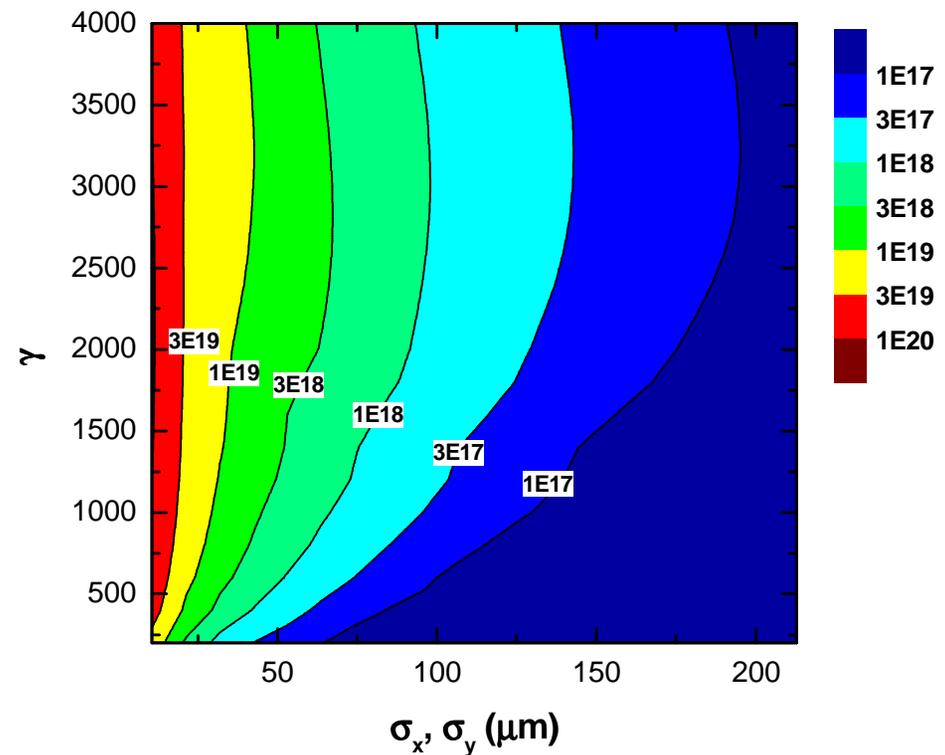
$$\approx \frac{\sqrt{2} \Sigma_0}{16\pi^3} \frac{N_p N_e}{\sigma_x \sigma_y \sigma_z \tau_L} \frac{\delta_{BW}}{\lambda}$$

### Parameters

$\sigma_z = 0.212$  ps  
 $\epsilon_n = 10^{-5}$  m rad  
 1 nC charge  
  
 $\tau_L = 8.6$  fs (FWHM 20)  
 $\lambda_L = 800$  nm  
 2 J per pulse  
  
 E=8 keV

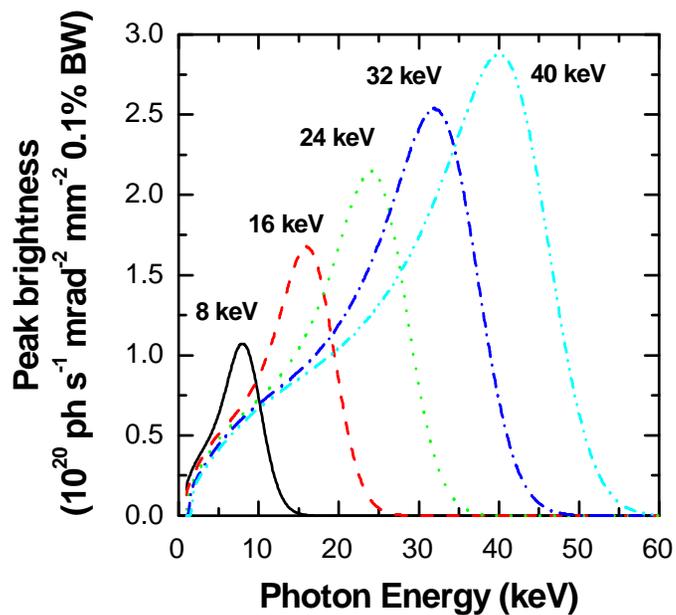
## Peak spectral brightness

Photons  $s^{-1} mm^{-2} mrad^{-2}$  per 0.1% BW

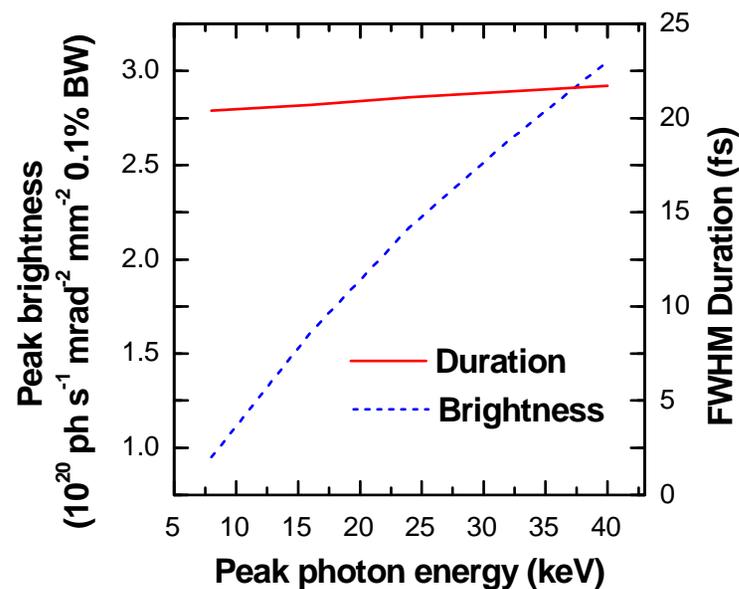


# X-ray tunability

## Sample spectra



## Brightness and duration



Bunch Energy	650 MeV
Beta function	1.5 cm
Emittance	10 $\mu$ m
Laser	20-fs, 2-J @ 800 nm

# X-ray pulse shaping



# Comparison

	APS Linac <sup>a</sup>	ALS 90 TS <sup>b</sup>	ALS Slicing <sup>c</sup>	Laser plasma <sup>d</sup>
Wavelength (Å)	1.5-0.4	0.4	6	1-10
Rep rate (Hz)	6	100	10 <sup>5</sup>	10
<b>Pulse length (fs)</b>	<b>20</b>	300	~100	~300
Average flux <sup>e</sup>	5×10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>7</sup>	10 <sup>9</sup>
Divergence (mrad)	3	10	0.6	4π sr
<b>Peak brightness <sup>f</sup></b>	<b>~10<sup>20</sup></b>	~10 <sup>16</sup>	~10 <sup>19</sup>	~10 <sup>18</sup>

- a. Predicted, with a **6-Hz, 20-fs, 2-J**, 800-nm laser at 650 MeV beam energy
- b. Schoenlein *et al*, *Science* **274**, 236 (1996), calculation
- c. Schoenlein *et al*, *Science* **287**, 2237(2000), calculation
- d. Rousse *et al*, *Rev Modern Phys* **73**, 17 (2001), experimental estimate
- e. In photons s<sup>-1</sup> per 0.1% BW
- f. In photons s<sup>-1</sup> mm<sup>-2</sup> mrad<sup>-2</sup> per 0.1% BW

# Case at APS: a realistic scenario

## Electron

Energy	200-650 MeV
Energy spread	0.1%
Charge per bunch	1 nC
Bunch length	0.2-3 ps
Normalized Emittance	3-10 $\mu\text{m}$
Rep Rate	6 Hz
Timing jitter	$\sim 1$ ps

## Laser

Pulse energy	1.4 mJ
Pulse duration	$< 50$ fs (FWHM)
Timing jitter	$< 1$ ps
Rep rate	1 kHz



$E=650$ MeV		
$\beta_{x,y}=0.015$ m		
$\epsilon_n$	10 $\mu\text{m}$	3 $\mu\text{m}$
$\sigma_{x,y}$	11 $\mu\text{m}$	6 $\mu\text{m}$
$\sigma_{x',y'}$	0.7 mrad	0.4 mrad



## X-ray Performance

$\tau$	50 fs (FWHM)
E	8-40 keV
$B_{\text{peak}}$	$\sim 10^{17}$
F	$\sim 10^2$



**Application !!!**

## Issues

- Interleaving of LINAC and Booster
  - Technically possible but PC gun drive laser reliability must be improved
  - Linac can handle 30 Hz, drive laser cannot
  - Stability of the LINAC and laser both are problematic for now
- Cost vs. benefit
  - Limited availability (competing with operation and machine study) unless interleaving
  - Interleaving can impact the ring operation if laser reliability is not significantly improved
  - Relatively low performance source in spectrum and divergence except for the pulse duration
  - Can serve as a prototype for the APS short pulse project

## Summary

- 1. In small-angle Thomson scattering the duration of the X-ray pulse closely follows that of the incident laser pulse, make 10-20 fs X-ray pulse duration possible.**
- 2. With the high quality electron bunches in combination with high power tabletop laser systems, high-brightness keV x-ray radiation can be generated.**
- 3. X-ray pulse can be shaped through laser pulse manipulation.**